

# Reevaluating reactor antineutrino anomalies with updated flux predictions

Jeffrey M. Berryman<sup>1,2,3</sup> and Patrick Huber<sup>1</sup>

<sup>1</sup>*Center for Neutrino Physics, Department of Physics, Virginia Tech, Blacksburg, Virginia 24061, USA*

<sup>2</sup>*Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506, USA*

<sup>3</sup>*Department of Physics, University of California, Berkeley, California 94720, USA*



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Hints for the existence of a sterile neutrino at nuclear reactors are reexamined using two updated predictions for the fluxes of antineutrinos produced in fissions. These new predictions diverge in their preference for the rate deficit anomaly, relative to previous analyses, but the anomaly in the ratios of measured antineutrino spectra persists. We comment on upcoming experiments and their ability to probe the preferred region of the sterile-neutrino parameter space in the electron neutrino disappearance channel.

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## I. INTRODUCTION

The evidence for the existence of additional neutrino species, which we generically call “sterile neutrinos,” can be broadly decomposed into three classes: anomalous  $\bar{\nu}_e$  disappearance at reactors [1]; anomalous  $\nu_e$  disappearance at GALLEX [2] and SAGE [3], i.e., the gallium anomaly; and anomalous  $\bar{\nu}_e$  appearance at LSND [4] and MiniBooNE [5]. These individual pieces, however, do not form a consistent whole. The reactor and gallium anomalies were found to be compatible at only the 9% level in Ref. [6]. Moreover, the combination of these and the absence of anomalous  $\nu_\mu/\bar{\nu}_\mu$  disappearance is incongruous with the LSND and MiniBooNE appearance anomalies. For recent reviews on the status of light sterile neutrinos, see Refs. [7,8].

It is natural to consider, then, why this picture breaks down. While models of new physics have been proposed to explain these anomalies [9–16], an obvious starting point is to scrutinize each to establish how robust it really is. Regarding the gallium anomaly, the  $^{71}\text{Ga}(\nu_e, e^-)^{71}\text{Ge}$  cross section has recently been reevaluated in Ref. [17] using an updated shell-model calculation. The preference for a sterile neutrino is weaker than for previous calculations, but the compatibility between the gallium and reactor anomalies is improved to 16% [17]. On the other hand, the LSND and MiniBooNE anomalies will be extensively probed by the upcoming short-baseline program at Fermilab [18,19]. In this paper, we focus on the electron neutrino *disappearance* channel.

We have reevaluated the reactor antineutrino anomaly (RAA) using updated predictions for the reactor antineutrino fluxes. The RAA comprises two parts: a deficit in the observed number of  $\bar{\nu}_e$  interactions relative to predictions and the existence of features in measured  $\bar{\nu}_e$  spectral ratios. We address both of these in what follows. Our results are obtained with the publicly available software GLOBES [20,21]; the underlying data libraries will be published in an accompanying software paper [22].

## II. UPDATED FLUX PREDICTIONS

Over the past decade, the Huber-Mueller (HM)  $\bar{\nu}_e$  flux predictions [23,24] have been the standard fluxes for calculations at reactors. These are derived from measurements of the aggregate  $\beta$  spectra from the products of nuclear fissions [25–27]. These  $\beta$  spectra are then converted to obtain predictions for the corresponding  $\bar{\nu}_e$  spectra using virtual  $\beta$  branches; see Refs. [23,24] for details. While the physics that enters into this procedure is broadly well understood, we highlight two sources of systematic uncertainty. (1) The accuracy of the underlying data. It cannot be excluded that there may be unaccounted for systematics in the measurements of aggregate  $\beta$  spectra that bias the results. (2) The theoretical understanding of the component  $\beta$  decays. The conversion procedure assumes that all  $\beta$  decays are of allowed type. However, a large fraction—up to 40%—of all decays are so-called forbidden decays. This introduces large uncertainties related to nuclear structure.

An alternative to the conversion method exists in the *ab initio* method. Here, one adds the spectra from every accessible  $\beta$  branch of every fission fragment, with appropriate weights determined by the cumulative fission fraction of each isotope, to determine the overall  $\beta$  spectrum.

However, this technique is similarly reliant on experimental data, both for the strengths of the individual

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$\beta$  branches and for the fission yields, which have historically been lacking. In recent years, the  $\beta$  feeding data have been revisited and improved using total absorption gamma spectroscopy (TAGS); see, e.g., Ref. [28]. Furthermore, *ab initio* calculations are also dependent on a theoretical understanding of forbidden decays.

Two new antineutrino flux predictions have recently appeared in the literature. An updated *ab initio* calculation was recently published in Ref. [28]. There, it was found that *ab initio* predictions produce better agreement with the  $\bar{\nu}_e$  spectrum measured at Daya Bay than the HM predictions. This is due, in large part, to a  $\sim 10\%$  reduction in the flux from  $^{235}\text{U}$ , a feature that is consistent with previous findings [29,30]. The improvement largely stems from the improved  $\beta$  spectrum feeding functions. However, these calculations do not go beyond the allowed approximation.

An updated conversion method calculation has been presented in Ref. [31]; we refer to this calculation as “HKSS” in the remainder of this work. The significant improvement in HKSS is that forbidden decays are included via nuclear shell model calculations, allowing the authors to derive the relevant shape factors. The authors find an enhancement of the antineutrino flux at energies above 4 MeV relative to HM, somewhat mitigating the size of the infamous 5 MeV bump [30,32–34] and increasing the predicted antineutrino flux.

We have considered the impact of all three of these flux predictions on the preference of the global reactor antineutrino dataset for a sterile neutrino. An important factor in these analyses is the size of the theoretical uncertainties on the flux predictions. The HKSS flux predictions are published with uncertainties; see the appendix to Ref. [31]. In our calculations, we use the uncertainties from their parametrized results. The *ab initio* fluxes, however, have no stated uncertainties. In the absence of a more compelling option, we assign the fractional uncertainties on the HM predictions to the *ab initio* predictions in our analysis. This is an optimistic assignment of uncertainties; we will argue, however, that this does not affect the conclusions of this work.

### III. THE RATE ANOMALY

We begin with combined analyses of the inverse beta decay (IBD) event rates measured at the short-baseline experiments at Bugey [35,36], Gösgen [37], ILL [38,39], Krasnoyarsk [40–42], Nucifer [43], Savannah River [44], and Rovno [45,46]. Additionally, we analyze Chooz [47], Double Chooz [34], and Palo Verde [48,49] at medium baselines, as well as fuel evolution results from Daya Bay [50] and RENO [51,52]. We highlight the salient features of our analysis here; see Ref. [22] for more details.

Our analysis is constructed using ratios of the IBD rates measured at these experiments relative to the three-neutrino predictions for the three reactor antineutrino flux models mentioned previously. We use GLOBES to calculate the total

event rate at each experiment as a function of two sterile-neutrino parameters—the effective mixing angle  $\sin^2 2\theta_{ee}$  and the mass-squared splitting  $\Delta m_{41}^2$ . For short-baseline experiments, we use the two-flavor approximation for the survival probability,

$$P_{ee} \approx 1 - \sin^2 2\theta_{ee} \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E_\nu} \right). \quad (1)$$

For the medium-baseline experiments, we use the full four-flavor oscillation formalism with the best-fit values for the usual three-neutrino oscillation parameters from Ref. [53].<sup>1</sup>

The differences between the experimental and predicted ratios are combined into a global  $\chi^2$  function,

$$\chi^2 = (\vec{R}_{\text{exp}} - \vec{R}_{\text{pred}})^T \cdot V_{\text{exp}}^{-1} \cdot (\vec{R}_{\text{exp}} - \vec{R}_{\text{pred}}) + \vec{\xi}^T \cdot V_{\text{th}}^{-1} \cdot \vec{\xi}, \quad (2)$$

where  $\vec{R}_{\text{exp}}$  is the vector of experimental ratios,  $\vec{R}_{\text{pred}} = \vec{R}_{\text{pred}}(\sin^2 2\theta_{ee}, \Delta m_{41}^2, \vec{\xi})$  is the vector of predicted ratios, and  $\vec{\xi}$  is a vector of nuisance parameters describing the normalization uncertainties on the isotopic flux predictions—one each for  $^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{239}\text{Pu}$ , and  $^{241}\text{Pu}$ . Further,  $V_{\text{exp}}$  is the covariance matrix describing experimental uncertainties, including correlations, and  $V_{\text{th}}$  is the covariance matrix for  $\vec{\xi}$ . We minimize over the  $\vec{\xi}$  for each point in  $\sin^2 2\theta_{ee}$ – $\Delta m_{41}^2$  parameter space.

We cross-check our results with the HM flux model against the *rate* results in Refs. [1,6,54–57]. We find generally good agreement; the resulting 95% C.L. curve is shown in orange in Fig. 1. The HM fluxes are then replaced in favor of the *ab initio* and HKSS fluxes and the analysis is repeated; the resulting 95% C.L. curves are shown, respectively, in blue and dark cyan in Fig. 1. For context, we show the region preferred by the gallium anomaly at 90% C.L. [17] in shaded purple.

The updated flux models diverge, relative to the HM fluxes, in their preference for a sterile neutrino. On one hand, the *ab initio* fluxes indicate a much *weaker* preference for a sterile neutrino; these fluxes prefer nonzero mixing at  $< 1\sigma$ . This can be largely attributed to the reduced total flux from  $^{235}\text{U}$  fissions relative to the HM predictions, as mentioned above. Further, recall that assigning the HM uncertainties to the *ab initio* fluxes underestimates the true theoretical uncertainty. A more realistic error budget would further degrade the preference for a sterile neutrino. On the other hand, the HKSS predictions result in *stronger* evidence for a sterile neutrino: recalculating the shape factor accounting for forbidden decays results in an increased expected IBD rate, implying

<sup>1</sup>We assume that the existence of a sterile neutrino has not caused any of these parameters to be mismeasured.

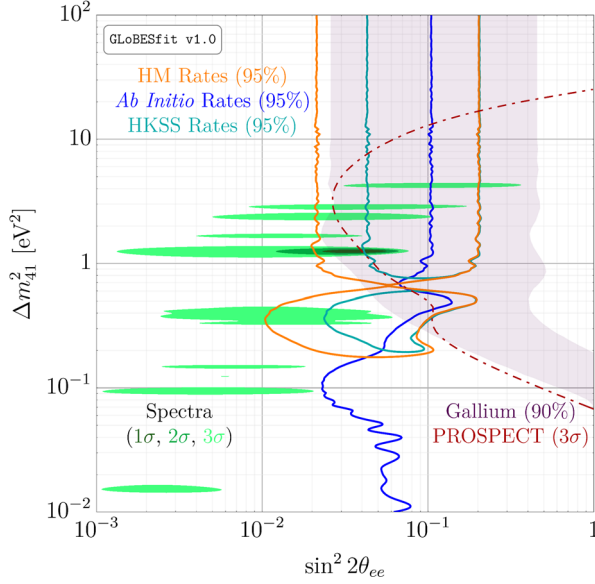


FIG. 1. The 95% C.L. contours from IBD rate measurements using the HM (orange), *ab initio* (blue), and HKSS (dark cyan) flux predictions. The regions preferred by reactor antineutrino spectra at  $1\sigma$ ,  $2\sigma$ , and  $3\sigma$  are shown in light, medium, and dark green, respectively. We show the 90% C.L. region preferred by the gallium anomaly [17] for comparison. The red, dot-dashed curve shows the  $3\sigma$  sensitivity of PROSPECT [58] assuming 3 years of operation.

larger experimental deficits. Relevant statistics for these analyses are compiled in Table I.

We underscore that the diverging preference for a sterile neutrino between the *ab initio* and HKSS flux predictions highlights the need to reappraise the data underpinning these predictions. As of present, improved TAGS measurements in the *ab initio* model and the more complete treatment of forbidden decays in HKSS modify the total predicted rate to roughly the same degree but with opposite signs. Concerns about vastly increased uncertainties from first-forbidden decays [59] seem not to be borne out in the detailed analysis in HKSS. That said, these conclusions can only be solidified with the collection of more and improved

TABLE I. A summary of relevant statistics in our analyses. We show  $\chi^2$  for  $\sin^2 2\theta_{ee} = 0$ ,  $\chi^2_{3\nu}$ , and the minimum value of  $\chi^2$  over the sterile neutrino parameter space,  $\chi^2_{\min}$ . We also tabulate the number of data points for each analysis,  $n_{\text{data}}$ , the  $p$ -value at which three-neutrino mixing can be excluded and the number of  $\sigma$  corresponding to that  $p$ -value.

Analysis	$\chi^2_{3\nu}$	$\chi^2_{\min}$	$n_{\text{data}}$	$p$	$n\sigma$
HM rates	41.4	33.5	40	$2.0 \times 10^{-2}$	2.3
<i>Ab initio</i> rates	39.2	37.0	40	0.34	0.95
HKSS rates	58.1	47.5	40	$5.0 \times 10^{-3}$	2.8
Spectra	184.9	172.2	212	$1.8 \times 10^{-3}$	3.1
DANSS + NEOS	98.9	84.9	84	$9.2 \times 10^{-4}$	3.3
DANSS' + NEOS	113.7	103.0	96	$4.7 \times 10^{-3}$	2.8

data. Until then, this inconclusiveness—that these two new predictions produce diverging evidence relative to HM—is a primary conclusion of this work.

#### IV. THE SPECTRAL ANOMALY

We shift our attention to the reactor  $\bar{\nu}_e$  energy spectra measured at Bugey [36], DANSS [60], Daya Bay [61], Double Chooz [34], NEOS [32], and RENO [33]. With the exception of NEOS, each of these experiments measures the  $\bar{\nu}_e$  spectrum at multiple positions and publishes ratios of these spectra. The benefit of such ratios is that the dependence on the reactor flux model largely cancels, mitigating theoretical uncertainties. The NEOS Collaboration presents their spectrum as a ratio with respect to the spectrum measured at Daya Bay in Ref. [62], which introduces mild flux model dependence into the analysis; see Ref. [22] for details.

PROSPECT [63] and STEREO [64,65] have also produced constraints in the last few years. Given that these experiments are still collecting data and that only limited information on how to include them in a global fit is available, we choose not to include them here, but discuss their expected impact below.

The two-flavor approximation in Eq. (1) is used for Bugey, DANSS, and NEOS, but we use the full four-neutrino framework for Daya Bay, Double Chooz, and RENO. These spectral ratios are combined in a single  $\chi^2$  function of the form

$$\chi^2 = \sum_A (\vec{S}_{\text{exp}}^A - \vec{S}_{\text{pred}}^A)^T \cdot (V_A)^{-1} \cdot (\vec{S}_{\text{exp}}^A - \vec{S}_{\text{pred}}^A), \quad (3)$$

where  $A$  indexes the experiments,  $\vec{S}_{\text{exp}}^A$  is the experimental spectral ratio, and  $\vec{S}_{\text{pred}}^A = \vec{S}_{\text{pred}}^A(\sin^2 2\theta_{ee}, \Delta m_{41}^2)$  is the predicted spectral ratio. Each experiment has its own covariance matrix  $V_A$  that includes both experimental and theoretical uncertainties. In principle, all experiments are correlated through the theoretical uncertainties. Practically speaking, these correlations are negligible.

The  $\chi^2$  is calculated at each point in the  $\sin^2 2\theta_{ee}$ – $\Delta m_{41}^2$  parameter space; the results are shown in Fig. 1. The  $1\sigma$ ,  $2\sigma$ , and  $3\sigma$  preferred regions are shown in dark, medium, and light green, respectively and are consistent with similar results in Refs. [6,29,56]. The sensitivity is primarily driven by DANSS; the total evidence for a sterile neutrino is  $3.1\sigma$ . It is noteworthy that NEOS and DANSS point to the same  $\Delta m_{41}^2$  despite their baselines differing by a factor of two. Relevant statistics are compiled in Table I.

Recently, the DANSS Collaboration has presented preliminary results for their expanded dataset, including an improved treatment of systematic uncertainties. We have investigated how these data can be expected to modify this analysis. In the last row of Table I, we show relevant statistics for the combination of this new dataset (which we



call “DANSS”) with NEOS. The overall significance from these data weakens from  $3.3\sigma$  to  $2.8\sigma$ ; the evidence for a sterile neutrino is lessened, but not altogether washed out. We anticipate revisiting these data upon official publication from the collaboration.

We do not combine our rate and spectral analyses; there are nontrivial correlations that would need to be taken into account that are difficult to estimate. However, one can infer from Fig. 1 that the spectral analysis is consistent with the *ab initio* analysis; the latter shows weak preference for a sterile neutrino, so consistency is essentially guaranteed. However, one can also infer that the tension between the spectral and HKSS analysis is greater than with the HM analysis. In this way, too, we see the *ab initio* and HKSS analyses diverge.

It has been suggested that the unexplained feature at 5 MeV in the prompt energy spectrum may influence the inferred evidence for a sterile neutrino. We have performed additional analyses in which additional Gaussian contributions have been added to the HM predictions for  $^{235}\text{U}$  and  $^{239}\text{Pu}$ . These features are taken to have a common central position (5.8 MeV antineutrino energy) and width (0.5 MeV), but they have different magnitudes. These have been determined by comparison with the spectral measurements in Refs. [30,51,66]; see Ref. [22] for more details. We find that the evidence for a sterile neutrino does not meaningfully change in the presence of this bump, for neither rate nor spectral measurements.

## V. FUTURE EXPERIMENTS

It is useful and imperative to consider how this parameter space can be probed in the near term, given the uncertainty surrounding analyses of the rates but the apparent robustness of spectral measurements. We consider only experiments searching for  $\nu_e/\bar{\nu}_e$  disappearance; for discussions on the future of  $\nu_e/\bar{\nu}_e$  appearance and  $\nu_\mu/\bar{\nu}_\mu$  appearance/disappearance, see Refs. [7,8].

We begin with PROSPECT and STEREO, which have produced early results [63–65], but not, at present, final analyses. These experiments were designed in the first half of the decade to conclusively probe the RAA as presented in Ref. [1]; early results indicate that they will achieve this. However, since these experiments were conceived, reactor spectrum experiments have shifted the preferred sterile neutrino parameters to smaller mixing angles than previously indicated.

We use PROSPECT as proxy to study how well current-generation reactor experiments can probe the regions preferred by the four global analyses presented here. The expected  $3\sigma$  sensitivity for 3 years of operation is shown in dot-dashed dark red in Fig. 1 [58]. This sensitivity represents a prediction of how a null result from PROSPECT, i.e., the nonobservation of oscillations, would constrain the parameter space. The question, then, is how much of the currently allowed regions would survive? To

quantify this, we calculate the difference between the three-neutrino  $\chi^2$ ,  $\chi^2_{3\nu}$ , and the minimum four-neutrino  $\chi^2$  for fixed  $\Delta m^2_{41}$ ,  $\chi^2_{\min}(\Delta m^2_{41})$ —a measure of the preference the data show for oscillations with a given  $\Delta m^2_{41}$ —for each analysis presented here. We consider how a null result from PROSPECT would reduce this quantity and hence, how much the allowed parameter space is reduced.

The results are shown in Fig. 2. The dashed curves show  $\chi^2_{3\nu} - \chi^2_{\min}(\Delta m^2_{41})$  for the HM rates (orange), *ab initio* rates (blue), HKSS rates (dark cyan), and spectra (black) analyses with no contribution from PROSPECT. The solid curves are similar, except PROSPECT’s sensitivity has been folded in. In regions where the difference between the dashed and solid curves of a given color is large, PROSPECT reduces the allowed parameter space significantly. PROSPECT is effective at probing the HM and HKSS rate analyses in the region  $\Delta m^2_{41} \sim 1\text{--}10 \text{ eV}^2$ ; this is precisely the region of parameter space for which it was designed. Conversely, PROSPECT does little to challenge the *ab initio* rate analysis, since this produces weak preference for a sterile neutrino in the first place.

Most interesting is its sensitivity to the spectral anomaly. Measurements of spectral ratios are susceptible to statistical fluctuations that essentially guarantee a best-fit point at nonzero mixing; see Ref. [67] for more discussion. Consequently, we advocate taking a broader view of the preferred parameter space when considering the impact of PROSPECT on the spectral anomaly. PROSPECT is strongest in probing the region  $\Delta m^2_{41} \sim 1\text{--}5 \text{ eV}^2$ , similar to the HM and HKSS analyses. However, it only has modest power to probe the region  $\Delta m^2_{41} \sim 0.1\text{--}0.5$ , where the preference for a sterile neutrino is also nontrivial.

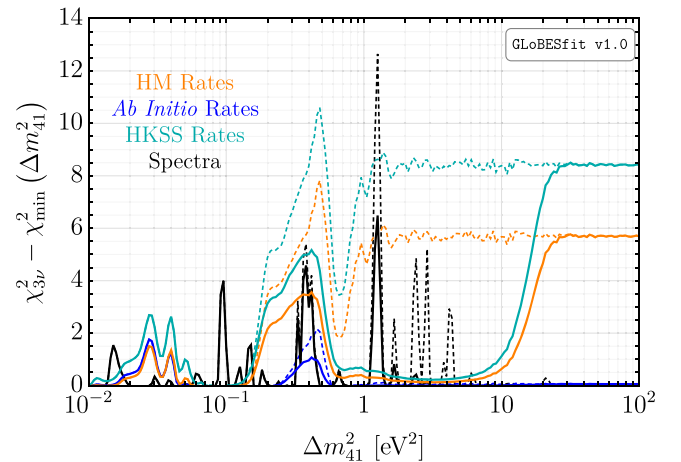


FIG. 2. The difference between the three-neutrino  $\chi^2$ ,  $\chi^2_{3\nu}$ , and the minimum four-neutrino  $\chi^2$  for a fixed  $\Delta m^2_{41}$ ,  $\chi^2_{\min}(\Delta m^2_{41})$ . The dashed lines are for the four global analyses presented here: HM rates (orange), *ab initio* rates (blue), HKSS rates (dark cyan) and spectra (black); the solid lines show the remaining preference for oscillation after the inclusion of a hypothetical null result from PROSPECT.

Overall, a  $2.4\sigma$  preference for oscillation would remain even after a null result from PROSPECT. Consequently, additional experimentation would be required to more fully probe the preferred parameter space.

IsoDAR [68], which proposes to use a high-intensity  $\bar{\nu}_e$  source from  $\beta$  decays of  $^8\text{Li}$ , has an expected  $5\sigma$  sensitivity [7] that suggests it has the potential to emphatically confirm or refute the sterile-neutrino interpretation of the RAA. There also exists a burgeoning program of experiments searching for coherent elastic neutrino-nucleus scattering [69–78] that may be able to probe the anomaly [79,80] at high significance, though this process has not yet been observed at a nuclear reactor.

## VI. CONCLUSIONS

We have reanalyzed the global reactor  $\bar{\nu}_e$  dataset using three reactor antineutrino flux predictions. Relative to the traditional HM predictions, the two new calculations result in diverging evidence for a sterile neutrino when total IBD rate measurements are considered—the *ab initio* calculation decreases the significance from  $2.3\sigma$  to  $< 1\sigma$ , whereas the HKSS calculation increases the significance to  $2.8\sigma$ . However, the spectral anomaly is robust with respect to varying the flux model and is found to persist at the  $3.1\sigma$  level.

We have shown that null results from current reactor experiments—PROSPECT, in particular—would leave a significant fraction of the currently favored parameter space unexplored. Proclamations of the demise of the light sterile neutrino are, therefore, premature. Given the current evidence for the existence of light sterile neutrinos, it is crucial that the next generation of oscillation experiments includes an effective strategy for probing the sterile neutrino hypothesis in the electron neutrino disappearance channel.

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